JUN 30 1986

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NOTE TO: Philip S. Justus, Acting Chief
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THRU: Myron H. Fliegel, Section Leader
Hydrology Section, WMGT

FROM: Richard Codell
Hydrology Section, WMGT

SUBJECT: SUPPORTING ANALYSIS FOR FEA COMMENT ON GROUNDWATER TRAVEL TIME IN YUCCA MOUNTAIN FEA

I have reviewed the discussion on groundwater travel time presented in the Yucca Mountain FEA. The model used for groundwater flow through the unsaturated zone is inappropriate, in my opinion. The attached report documents, in some detail, my review of the model and the way it has been applied. Parts of the report will be included in a major staff comment. I would be glad to brief you on this or any other part of the major comment on groundwater travel time.

/S/
Richard Codell
Hydrology Section, WMGT

WM Record File 102
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PDR ✓
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Supporting Analysis for FEA Comment
on Groundwater Travel Time
Yucca Mountain Site

by
Richard Codell

Introduction

The Department of Energy presents an analysis for groundwater travel time (GWTT) through the unsaturated zone at the Yucca Mountain site. The analysis is for steady state flow in the vertical direction through several unsaturated hydrogeologic units from the underground facility to the regional water table. The thicknesses of the hydrogeologic units varies over the area covered by the underground facility. DOE analysed the travel time by considering that the repository area is subdivided into 963 vertical columns, 250 ft. on a side as shown in Fig. 6-5 from the FEA. A GWTT distribution for the site is calculated by performing multiple monte carlo runs (or "realizations") for each of the 963 columns. Each run calculates a groundwater travel time for a column by imposing a vertical flux of 0.5 mm/yr, and calculating the travel time through succeeding layers of tuff. The GWTT distribution is then generated from the ensemble of all runs. The distribution so determined contains both the real variation of travel time caused by the spatial variation of tuff thickness, and also the variations caused by the range of measured values in the hydrogeologic properties of the layers.

The vertical columns are subdivided into up to seven hydrogeologic units, which are further subdivided into 10 ft. layers. The saturated hydraulic conductivities of the layers beneath the repository plane are chosen by statistically sampling from an assumed range for each hydrogeologic unit. If the hydraulic conductivity for the layer is less than 0.95 of the flux, flow is assumed to be entirely in the matrix. Velocity in the ith layer is calculated:

$$V_i = (q/n_e)(q/K_s)^{-1/\varepsilon} \qquad (1)$$

where q is the flux = 0.5 mm/yr
n_e is the effective porosity
K_s is the saturated hydraulic conductivity
and ε is a correction factor.

Effective porosity and hydraulic conductivity are chosen from assumed distributions for each random realization. The coefficient ε is a constant for each major hydrogeologic unit.

If the assumed flux is greater than 95% of the sampled hydraulic conductivity of the layer, flow in excess of that which can be carried in the matrix is assumed to move in the fractures. The fracture velocity in the layer for this case is:

$$V_i = (q-K_s)/0.0001 \qquad (2)$$

where 0.0001 is the assumed pore space for fracture flow. The travel time in the matrix is calculated using Eq.1, with K_s substituted for q. The shorter of the two travel times is chosen to represent the layer.

DOE also performed an analysis for the problem (method 2) in which each hydrogeologic unit represents one layer; i.e., the layer spacing is much greater than that assumed in method 1. DOE makes the claim that method 2 is more conservative than method 1 because "as more physical realism is introduced into the travel time model, the range of travel times is likely to be compressed. Moving from method 2 to method 1 clearly has the effect of removing the low probability, extreme values in the tails of the frequency distribution of travel times from the disturbed zone to the water table "(FEA, p. 6-162). The cumulative frequency distributions (CDF) for method 1 and method 2 are shown in FEA Fig. 6-9. DOE shows that method 2 gives more conservative GWTT for the small percentiles of the CDF. Method 1, which is supposedly more realistic is clearly more favorable to DOE's case.

Analysis

Values of the parameters of the model are criticized in the FEA comments. In particular, the assumed distribution of the hydraulic conductivity and the flux might not be conservative. The present review, however, is concerned only with the possible errors in the model itself and the way that the model has been employed to generate the GWTT probability distribution.

Unfortunately, the DOE analysis is seriously flawed. The supposed realism of method 1 over method 2 is nothing more than a mathematical artifact. It is likely, in fact, that method 2 is more realistic than method 1, or more precisely, more likely to include the correct GWTT distribution than method 1. The major problem with DOE's claim that method 1 is more accurate is that the individual layers within each unit are sampled randomly from assumed ranges of porosity and hydraulic conductivity within each hydrogeologic unit, with no spatial correlation assumed between layers. Thus, the properties in adjacent layers bear no resemblance, no matter how close the spacing. A high permeability layer may be directly adjacent to a layer with very low permeability in the DOE scheme. It is unlikely with this method that two layers with fracture flow would be found in contact.

In reality, the material properties in each hydrogeologic unit are likely to be spatial correlated, both vertically and horizontally, because the tuff layers were created in episodes of volcanic eruptions, each over relatively short spans of geologic time, and therefore would be moderately homogeneous.

The fallacy of DOE's arguments in support of method 1 can be demonstrated for a slightly simpler analog of the Yucca Mountain case. Only the spread in travel times caused by data uncertainty is demonstrated by this example. Consider

only a single hydrogeologic unit of uniform thickness L. Hydraulic conductivity and porosity are sampled from probability distributions to get the travel time for each layer. In method 1, the hydrogeologic unit is segmented into N layers, each with thickness L/N. In method 2, there is only one layer of thickness L. The velocity of groundwater in each layer is determined by the faster of either the matrix or fracture flow velocities through each layer. The probability distribution for the groundwater velocity V can be constructed from Eqs.1 and 2, any cross-correlation between n_e and K_s, and the rules for the transition from matrix to fracture flow. The same probability distribution for velocity applies to any layer in the column. The shape of the velocity distribution will be unusual and may be bimodal. The shape of the distribution is of no immediate concern to the present discussion. It is only important in that it can be defined for the column and sampled for each layer.

The GWTT distribution is created by generating multiple random realizations of the column. For the jth random realization of the model, the travel time is the sum of the individual travel times for each layer:

$$T^j = \sum_{i=1}^{N} t_i^j = \sum_{i=1}^{N} \Delta x/V_i^j = (L/N) \sum_{i=1}^{N} 1/V_i^j \qquad (3)$$

Several things are evident from Eq. 3. First, travel time T will be a normally (not lognormally) distributed variable because of the Central Limit Theorem, no matter what the distribution of 1/V. Furthermore, as the number of layers, N increases, the term:

$$(1/N)\sum_{i=1}^{N} 1/V_i^j$$

approaches the expected value <1/V>. In other words, in the limit of an infinite number of layers the travel time would not change from realization to realization. There would be only a single groundwater travel time (i.e., a "step change" GWTT distribution):

$$T^j = L \langle 1/V \rangle \qquad (4)$$

which according to DOE, would be "more realistic". This is, of course, not the case. The fallacy is that the layers are chosen independently from each other when actually they are spatially correlated at some scale.

The GWTT for the jth random realization using method 2 would be:

$$T^j = t = L(1/V)^j \qquad (5)$$

Travel time T would be a distributed value, with the same distribution as 1/V. Because of the likely spatial correlation of the physical properties in each hydrogeologic unit, the GWTT distribution from method 2 is more likely to encompass the correct GWTT value. In method 2, the spatial correlation is assumed to be perfect (i.e., for each realization the properties are uniform in the layer). All variation in GWTT is assumed, therefore, to be caused by uncertainty, leading to a wide and therefore more conservative distribution (at least in terms of the NRC position on pre-waste-emplacement groundwater travel time).

The actual Yucca Mountain case would be more complicated than the example demonstrated. The real variation in layer thickness depending on the location of the column on the site, would result in a spread of travel times irrespective of data uncertainty. In addition, considering multiple layers would cause an averaging effect on the travel time calculated for method 2, which would tend to make the GWTT distribution more normal and less like the distribution of 1/V (i.e., the Central Limit Theorem). Method 1 would still converge to a single groundwater travel time for each column for an infinite number of layers, however.

Conclusion

The DOE analyses for GWTT at the Yucca Mountain site is seriously flawed. In terms of the topics discussed in the present review, the DOE analysis could be improved by demonstrating the effect of vertical correlation scale on the GWTT distribution, and then estimating the likely scales of vertical correlation based on actual field data or analogous site data. If no correlation scales can be estimated, then the conservative point of view would require that method 2 be used in preference to method 1, because the former gives a wider GWTT distribution.

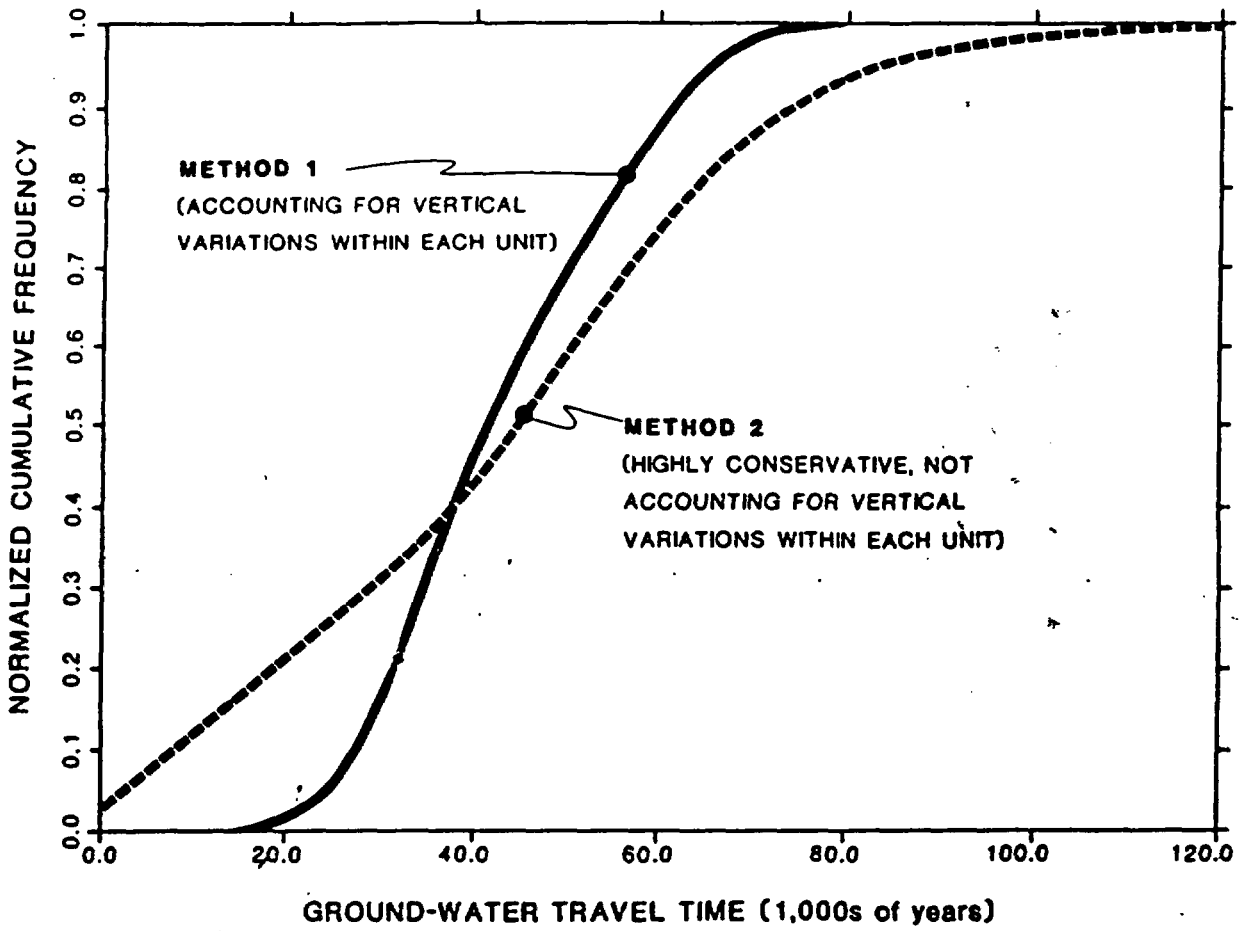

Figure 6-9. Cumulative frequency of travel times: Method 1—more realistic case; Method 2—more conservative, probably unrealistic, case. Flux is 0.5 millimeter (0.02 inch) per year for both cases. Modified from Sinnock et al. (1986).

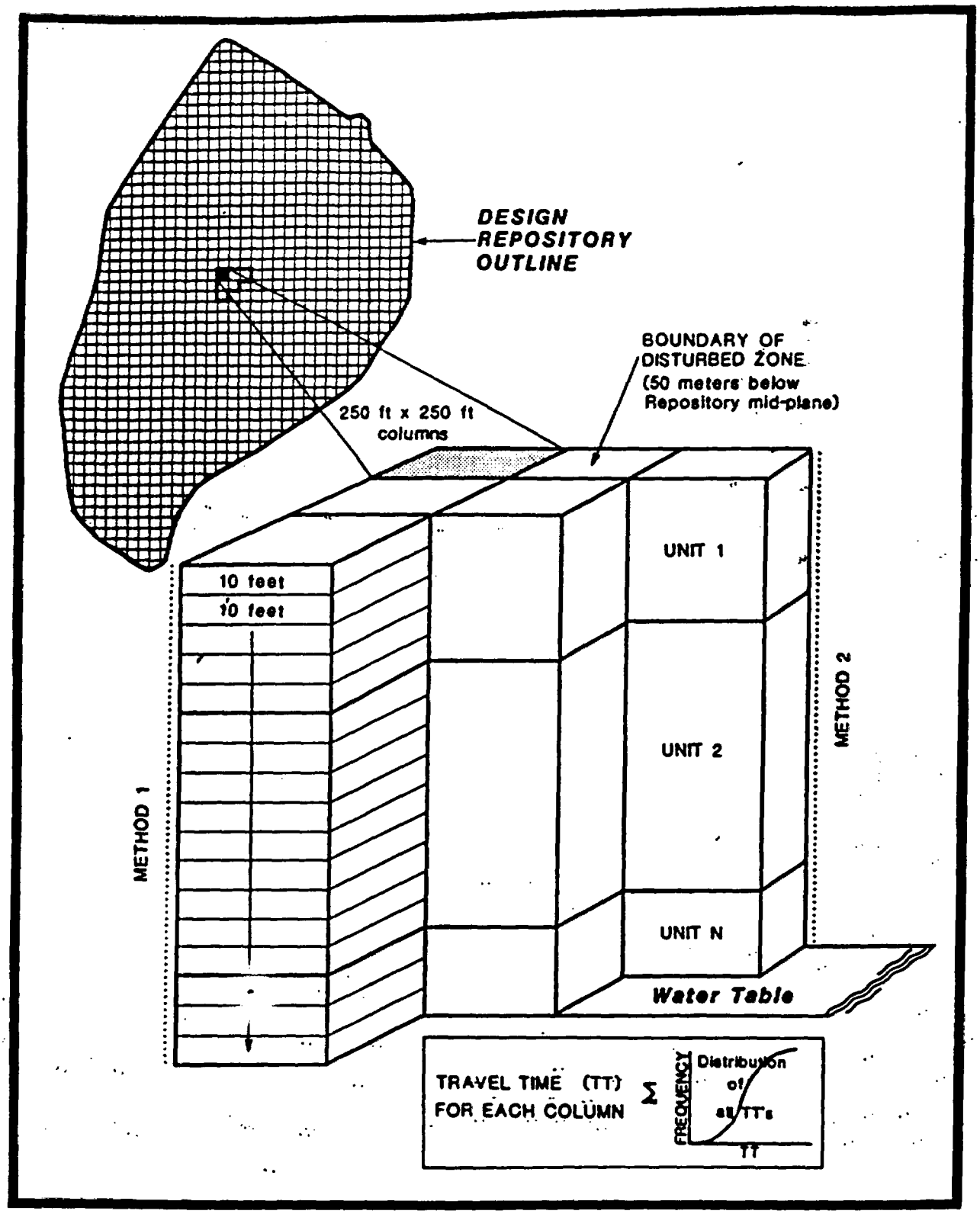

Figure 6-5. Schematic diagram illustrating three-dimensional geometry for multiple elements 10 feet thick. In Method 2, only 1 element is assigned to each unit and its thickness equals the unit thickness. Modified from Sinnock et al. (1986).